(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
Internati nal Bureau

(43) Internati nal Publication Date
28 December 2000 (28.12.2000)

PCT

(10) International Publication Number
WO 00/79319 A1

(51) International Patent Classification⁷: G02B 6/16, F21V 8/00

(21) International Application Number: PCT/CA00/00733

(22) International Filing Date: 16 June 2000 (16.06.2000)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
09/335,744 18 June 1999 (18.06.1999) US
09/517,433 2 March 2000 (02.03.2000) US

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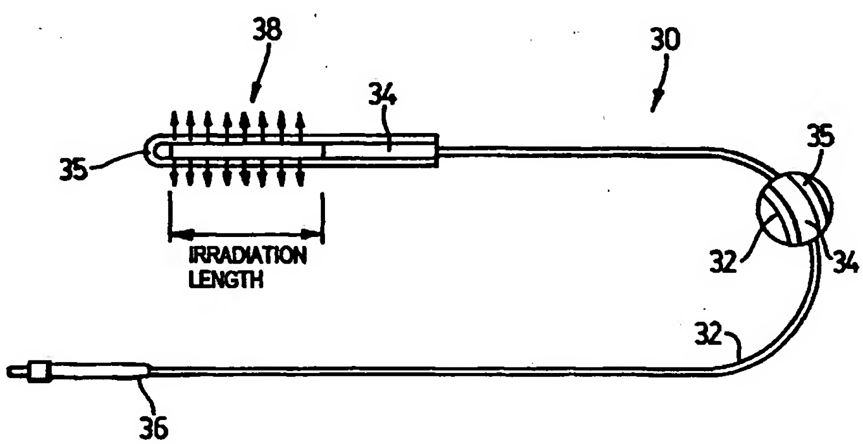
(81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CR, CU, CZ, DE, DK, DM, DZ, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, TZ, UA, UG, UZ, VN, YU, ZA, ZW.

(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GW, ML, MR, NE, SN, TD, TG).

Published:
— *With international search report.*
— *Before the expiration of the time limit for amending the claims and to be republished in the event of receipt of amendments.*

[Continued on next page]

(54) Title: OPTICAL FIBER DIFFUSER



(57) Abstract: Optical fiber diffusers for emitting light cylindrically along a length of the fiber diffuser (38) with preselected light intensity distributions along the length of the diffuser. The diffuser portion is defined by forming a distribution of scattering centers in a section of the optical fiber core (34) having a modulated index of refraction which acts to couple light radially out of the fiber along the diffuser section. The intensity distribution of light coupled out of the diffuser section of the fiber is controlled by controlling the profile of the modulated index of refraction, namely the coupling coefficient, along the length of the grating. Writing a grating into a multimode fiber provides a method of monitoring transmission in the fiber since some of the light can be coupled out and detected and interrogated. The diffuser devices can be used as sensors, since they also couple light incident on the diffuser into the core where it is transmitted to a detector.

WO 00/79319 A1

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

OPTICAL FIBER DIFFUSER

FIELD OF THE INVENTION

The pres nt invention r lates to optical fiber diffuser devices for emitting light along a length of the fiber diffuser, and more particularly the invention relates to optical fiber diffusers and methods of producing them with preselected light intensity distribution along the length of the diffuser.

BACKGROUND OF THE INVENTION

The use of optical fiber as a waveguide to deliver light from a light source to a remote location has long been considered desirable. A number of medical applications, such as photodynamic therapy, interstitial laser photo-coagulation or interstitial laser hyperthermia for tumor destruction, require a diffuser that emits laser light radially from the optical fiber. One of the main challenges of making such a device is to have the light emitted homogeneously along the length of the diffuser tip, especially for tips longer than 5.0 mm. In some applications the fiber diffuser needs to be thin enough to go through hollow-bore needles, catheters and endoscopes.

Present cylindrical fiber diffusers use micro-beads or Rayleigh scatterers distributed along the fiber tip to scatter the light radially. The amount of light scattered can be controlled by the size and density of microbeads. The diffuser outer diameters range from 0.356 to 1.4 mm (typically 1 mm). United States Patent Nos. 5,196,005 and 5,330,465 issued to Doiron et al. disclose such a diffuser tip having scattering centers embedded in a silicone extension that abuts the end of an optical fiber. The scattering centers are embedded in the silicone in such a way that they increase in density from the proximal end of the diffuser abutting the optical fiber to the distal end of the diffuser. United States Patent No. 5,269,777 issued to Doiron et al. discloses a diffuser tip having a silicone core

attachable to the end of an optical fiber. The cylindrical silicone xt nsion is coated with an outer silicon layer having scattering centers embedded therein.

United States Patent No. 5,643,253 issued to Baxter et al. is directed to an optical fiber diffuser including an attachment that abuts the end of an optical fiber. The diffuser includes a cylindrical polymeric section in which scattering centers are embedded.

United States Patent No. 4,986,628 issued to Lozbenko et al. teaches an optical fiber diffuser attachment that abuts the end of an optical fiber. The diffuser is made of an optically turbid medium which may be polymer based which is contained in a protective envelope or sheath that slides over the end of the optical fiber.

United States Patent No. 5,207,669 issued to Baker et al. discloses an optical fiber diffuser tip that abuts the end of an optical fiber for providing uniform illumination along the length of the diffuser tip. The diffuser section is produced by thinning the higher refractive index cladding surrounding the multimode fiber core so it has a thickness less than the penetration depth of the evanescent field to permit penetration of the cladding by the evanescent fields along the diffuser section. Some of the light propagating down the fiber core will therefore be emitted and some reflected back into the core at each point along the diffuser tip.

Single mode fibers with weak tilted phase gratings that couple light out of the fiber have been disclosed in T. Erdogan and J.E. Sipe, Tilted Fiber Phase Gratings, J. Opt. Soc. Am. A/Vol. 13, No. 2/February 1996.

There are several inherent disadvantages of these types of diffusers including difficulty in achieving illumination homogeneity for long diffusers, and that typically they are non-Lambertian emitters, many are restricted to use at the ends of the optical fiber, and the diffuser tips can break loose at high light intensity as have been observed and they are relatively expensive

in that separate diffuser tips have to be produced and adjoined to the nd of the optical fib r.

Therefore, th re is a n ed for optical diffusers that approximate Lambertian emission, are not limited to the ends of the fiber and do not require the assembly of separate component parts.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide an optical fiber diffuser device that can be produced in any portion of an optical fiber. It is also an objective of the present invention to provide an optical fiber diffuser device that is integrally formed with an optical fiber.

An advantage of the optical fiber diffuser devices constructed in accordance with the present invention is that they can be produced with variable intensity distributions along the length of the diffuser as required for the particular application for which the diffuser is designed. Another advantage of the diffusers is they are not attached to the end of the fiber as a separate piece but are formed anywhere along the optical fiber as part of the fiber itself.

The present invention provides an optical fiber diffuser device comprising;

an optical fiber having a core and a cladding surrounding the core, a distribution of scattering centers embedded in the core along a preselected length thereof defining a diffuser portion, the distribution of scattering centers having an effective density along said preselected length of the core for coupling optical radiation radially outwards from the diffuser portion with a preselected intensity distribution as a function of distance along the preselected length of the diffuser portion.

In this aspect of the invention the optical fiber may be a multimode optical fiber and the distribution of scattering centers may include a fiber

grating comprising an ffectiv modulated ind x of refraction profile along the preselected length of the core.

In another aspect of the invention there is provided an optical fib r device for delivery of photothermal energy, comprising:

a multimode optical fiber having a core and a cladding surrounding the core, a distribution of scattering centers embedded in the core along a preselected length thereof defining a diffuser portion, the distribution of scattering centers having an effective density along the preselected length of the core for coupling optical radiation radially outwards from the diffuser portion with a preselected intensity distribution as a function of distance along the preselected length of the diffuser portion; and

a source of optical radiation connected to one end of the multimode optical fiber.

In this aspect of the invention the optical fiber may be a multimode optical fiber and the distribution of scattering centers may include a fiber grating comprising an effective modulated index of refraction profile along the preselected length of the core. The fiber grating may be either a long period or a short period grating.

In another aspect of the present invention there is provided a method of producing an optical fiber diffuser device, comprising:

providing an optical fiber having a core and a cladding surrounding said core; and

calculating a coupling coefficient to produce a preselected intensity distribution of optical radiation to be radially emitted along a preselected length of the optical fiber; and

producing at least one distribution of scattering centers having an effective density along said preselected length of the core of the optical fiber for coupling optical radiation radially outwards from said diffuser portion with

said preselected intensity distribution as a function of distance along the length of th diffuser portion.

The present invention also provides an optical sensor, comprising:

a light detection means; and

an optical fiber connected to the light detection means, the optical fiber having a core and a cladding surrounding said core and including at least one distribution of scattering centers in a preselected length of the core, the distribution of scattering centers having an effective density along the preselected length of the core for optically coupling a fraction of light incident on the diffuser portion into the core which is transmitted to the light detection means.

In another aspect of the present invention there is provided a method of monitoring light signals transmitted along an optical fiber, comprising:

forming a distribution of scattering centers in a preselected length of an optical fiber, the distribution of scattering centers having an effective coupling strength to couple some of the light transmitted along core of the fiber out of the fiber and having an effective modulated index of refraction along the preselected length to give a desired intensity distribution of light emitted radially from the fiber; and

detecting light emitted from the fiber.

BRIEF DESCRIPTION OF THE DRAWINGS

Th invention will now be described, by way of non-limiting xampl s only, reference b ing had to the accompanying drawings, in which:

Figure 1 illustrates a multimode fiber with a grating-type diffuser formed in accordance with the present invention;

Figure 2 is a top view of a 50%-50% duty cycle uniform amplitude mask used for writing gratings in one embodiment of a the optical diffuser;

Figure 3 shows a 50%-50% duty cycle chirped amplitude mask used for writing gratings in another embodiment of an optical diffuser;

Figure 4 shows an optical illumination system including an optical fiber with a fiber diffuser formed at one end portion thereof;

Figure 5a is a plot of coupling coefficient as a function of position along a diffuser for emitting a uniform intensity along the diffuser;

Figure 5b shows a constant intensity distribution along a length of a fiber diffuser for the diffuser of Figure 5a;

Figure 6 is a plot of coupling coefficient as a function of position along a diffuser for emitting an intensity profile having a Gaussian distribution along the diffuser;

Figure 7 shows a Gaussian intensity distribution along a length of a fiber diffuser produced with the coupling coefficient of Figure 6;

Figure 8 is a diagrammatic representation of an optical diffuser with a buffer re-coat applied to the diffuser portion of the fiber containing fine particles for further scattering of light coupled out of the core;

Figure 9a is a polar plot of intensity distribution of light emitted from a grating-type fiber diffuser with the grating written from only one side of the fiber and with a polymer re-coat comprising SiO_2 powder;

Figure 9b shows an azimuthal plot of intensity distribution for the same fiber as in Figure 9a;

Figure 9c illustrat s a combined polar and azimuthal plot of int nsity distribution for a 3 mm l ngth grating-type optical diffuser produced by writing the grating in twice, the grating b ing re-written the second time after the fiber was rotated 90^0 with respect to the laser beam;

Figure 10 shows an alternative embodiment of a fiber diffuser constructed according to the present invention;

Figure 11 shows another alternative embodiment of a fiber diffuser; and

Figure 12 is a diagrammatic illustration of another embodiment of an optical fiber diffuser constructed in accordance with the present invention.

DETAILED DESCRIPTION OF THE INVENTION

The present invention provides a method of producing fiber diffusers directly in optical fibers thereby avoiding the deficiencies associated with separate fiber diffusers that are attached on the end of an optical fiber. When a focussed UV beam, for example from a KrF excimer laser, hits a single mode or multimode photosensitive fiber, a local change is induced in the refractive index of the fiber core. As the power of the UV beam and/or the exposure time increases, the intersection regions between areas of the fiber core exposed to the UV light and areas not exposed will begin to scatter light out of the fiber core if light is being transmitted down the fiber. Similarly, regions at the core/cladding interface exposed to the UV light may also act as scattering centers for light being transmitted down the core. This out-coupling of the guided light from the fiber core is due to the abrupt change in refractive index inside the core and/or due to physical defects generated at the core-cladding interface. The out-coupling of light from the fiber core increases with the total UV exposure.

When an appropriate distribution of these scattering centers is created in a section of an optical fiber, a very efficient fiber optical diffuser is

achi ved. In achi ving the d sired performance from the diffuser, the relative spatial relationship of scattering centers is not critical, but rath r the distribution of the density of scattering centers. Whil th location and the strength of the scattering centers can be locally random with an overall density distribution giving rise to the desired optical diffusion, the preferred embodiments discussed below pertain to relatively uniform structures due to their ease of use and the nature of available phase and amplitude masks used for writing fiber structures.

One exemplary method of producing the fiber diffusers disclosed herein is based on producing a modulated index of refraction along a length of the core of a singlemode or multimode fiber, $n + \Delta n$, in which n is the refractive index of the core and Δn is the change of the index. This portion of the fiber containing the modulated refractive index acts as a diffuser. The modulated refractive index portion of the fiber, referred to as a grating-type diffuser, is analagous to either a short period (Bragg) or a long period grating, depending on the period of the index modulation.

The refractive index modulation is typically produced by a uniform UV laser beam irradiating an optical fiber through an amplitude mask or a phase mask, or is produced by imprinting on the fiber an interference pattern generated by two-beam interference with a UV laser, to give a modulated index of refraction where n is the change of the index caused by the UV laser irradiation on a photosensitive single mode or multimode optical fiber. It is also possible, though not commonly done, to write the structure in a point by point fashion with a tightly focussed UV beam.

The so called Bragg or short-period grating, normally but not exclusively associated with a single mode optical fiber, comprises a periodic refractive index modulation along a portion of the single mode fiber with a periodicity of the order of 0.5 μm. These short period gratings are typically produced with phase masks. The Bragg grating couples the forward guided

mode into a backward guided mod and is therefore commonly referred to as a reflective filter.

As discussed above, the fib r Bragg grating comprises a periodic change in refractive index along the core of the fiber. These Bragg gratings are specifically designed to reflect specific wavelengths. At each period, a portion of the guided optical wave is reflected, interfering with other reflected components from the other periods in a constructive manner, see for example Meltz, G., Morey, W. W., Glen, W. H., **"Formation of Bragg Gratings In Optical Fibers By Transverse Holographic Method"**, Opt. Lett. 14(15) 813 (1989). In the present method the gratings are designed to couple light of all wavelengths out of the fiber, not to reflect specific wavelengths.

The technique used to imprint such a grating requires that the fiber be transversely exposed to a high power UV light. When the UV light passes through the phase mask put in front of the fiber, an interference pattern is produced, creating a structural change in the fiber core, which results in a permanent and stable modification of its refractive index. The refractive index profile through this portion reflects the properties of the phase mask.

In contrast to short period gratings, long period gratings have periods ranging anywhere from 20 μm to over 600 μm. Because the period is not of the order of the wavelength of the light, such a grating does not function as a reflective filter at any wavelength. To make gratings with these longer periods, the pattern can be laser machined directly as an amplitude mask, through which the fiber is illuminated by the UV laser. Other methods such as chemical etching or direct machining may be used to produce the amplitude masks. The amplitude masks are considerably less expensive and easier to use than phase masks.

In addition to differentiating gratings as short or long period, two distinct types of photo-induced changes have been identified based on

different exposures of UV light nergy. Type I gratings are based on the UV color center photosensitivity process. Type II gratings are based on the process of a UV-induced damage in the core-cladding interface area. In type II gratings, coupling between the guided core mode(s) and cladding modes can result in the light being coupled out from the fiber core into free space. Type I gratings are considered to be weaker gratings in the sense there is less of an abrupt refractive index change at the cladding/core interface. Conversely, type II gratings are much stronger gratings characterized by a much more abrupt change in refractive index at the cladding/core interface. These stronger gratings ensure significant light intensity is coupled or emitted out of the fiber.

The inventors have noted that type I gratings in multimode fibers also couple light out of the fiber but this configuration is characterized by much lower intensities, which may be useful for emitting light over very long lengths of the fiber. For medical PDT applications the much stronger type II gratings formed in the multimode fibers are preferred to give significantly higher emitted light intensities over shorter distances (typically up to several cm). Further, the inventors have noted that type I and type II also weakly couple light out of single-mode fibers, again with multimode fibers being the preferred embodiment. Therefore the present invention encompasses optical fiber diffuser devices with both long and short period gratings where both long and short period gratings may be type I or type II strength gratings.

Figure 1 shows a grating-type diffuser consisting of a grating 16 in a multimode optical fiber 12. The optical fiber 12 includes a fiber core 14 surrounded by a cladding 24 and a protective buffer layer 26. Long or short period gratings are generated in the fiber core 14, with a non-uniformity across the core dependant on the diameter of the core and focussing parameters of the UV laser beam used to write the grating. The gratings are written in by first removing the buffer layer 26 along the length of the

proposed diffuser. The grating is then written in, discussed more fully hereinaft r, aft r which a buffer re-coat 26' is reapplied to th fiber. The present diffus rs are just as flexible as normal communication fiber when th diffuser portion of the fiber is re-coated with buffer layer 26'.

The gratings in the present multimode fiber case are preferably created with much stronger refractive index modulations, preferably type II gratings as discussed hereinafter. Light is coupled by these strong gratings at the fiber core and cladding interface radially out of the diffuser portion.

In a preferred embodiment of the invention, an amplitude mask is used to produce long period gratings. Referring to Figure 2, an amplitude mask comprises an array of narrow slits or windows through which the laser beam passes into the fiber core. Exemplary, non-limiting masks used have included masks with 160 micron period, 50%-50% duty cycles, and result in an optical diffuser with good intensity distribution along the length of the diffuser. Amplitude masks with periods of down to 20 microns or less may be fabricated by laser micro-machining.

The intensity distribution of the UV laser light source may be controlled by passing the laser beam through an envelope-type amplitude mask prior to the light beam being focussed onto the optical fiber through the amplitude mask.

An alternative method is to use a chirped amplitude mask which results in a chirped grating. The chirped amplitude mask shown in Figure 3 is provided with varying window or slit periods along the length of the mask so a chirped grating with a modulated index of refraction commensurate with the mask is obtained. The use of a chirped grating type of diffuser is very advantageous because natural reduction in the intensity of light out-coupled along the length of the diffuser is compensated by an increased density of light-scattering-centers (i.e. modulation of the number of light out-coupling

points per unit length) along th diffuser inherently availabl with a chirped grating.

A significant advantag of using an amplitude mask compared to using a phase mask is cost since phase masks are typically much more expensive to produce than amplitude masks. A further advantage is that amplitude masks are far less susceptible to damage and are therefore easier to handle and maintain.

An optical fiber diffuser device constructed in accordance with the present invention is shown generally at 30 in Figure 4. The device includes a single or multimode optical fiber 32 having a fiber core 34 and cladding 35 (see the enlarged detailed section) and a screw mount assembly (SMA) connector 36 (or other standard connector) at one end of the fiber. The optical diffuser portion 38 of desired length L is formed at one end of the fiber. The diffuser 38 may comprise a long or short period grating or a predetermined density of scattering centers formed in the optical fiber 32. A laser beam at the desired wavelength is launched into optical fiber 32 through a fiber connector 36. The laser light is guided through the lead fiber 32 with a negligible loss and coupled out through diffuser 38 with the diffuser acting as a Lambertian emitter of optical radiation (typically 187 nm to about 10 microns wavelength). The end of the diffuser 38 may be terminated by an end coated silver mirror, or simply terminated in a cleaved end.

The amount of light coupled out of the fiber portion defining the diffuser is dependent on the strength and period of the grating (or strength and density of scattering centers). In the following discussion, reference is made to a grating-type diffuser, with the understanding that the principles also apply to any appropriate distribution of scattering centers written in the fiber core to form a diffuser. If the strength of the grating forming the diffuser is kept constant along the length of the diffuser, the total light intensity coupled out along the diffuser will follow the Beer-Lambert Law:

$$I = I_0\,[1-\exp(-KL)] \qquad (\ \text{q. } 1)$$

where I is the light intensity coupled out from the side of the fiber core, I_0 is the light intensity in th fiber core b fore the grating, K is the coupling coefficient and is proportional to the refractive index change (n) as well as the density of scattering centers or grating period, and L is the length of the diffuser.

The intensity distribution of light coupled out of the diffuser may be controlled by controlling the coupling coefficient along the diffuser. For example, a grating that couples light uniformly out of the fiber core along the length of the diffuser may be produced using a diffuser with a coupling coefficient K as shown in Figure 5a with Figure 5b showing the corresponding intensity distribution as a function of normalized position along the diffuser. Specifically, since the coupling coefficient increases with the fluence of the UV laser used to imprint the fiber gratings, by varying either the energy or the repetition rate of the laser pulses along the length of the grating, the coupling coefficient can be increased along the fiber as shown in Figure 5a (which shows a smoothed or idealized refractive index change (n) profile). A similar result can be achieved using a constant laser fluence by varying the density of scattering centers either through directly writing the pattern with a focussed laser or by writing a chirped grating. Thus, using the method of the present invention it is possible to custom design the coupling coefficient K as a function of location along the grating, and hence modulate the light output along the diffuser in any preselected profile.

In some medical applications it may be desirable to have a strong light dose that illuminates the center of a tissue volume and a reduced light dosage towards the edge similar to the Gaussian intensity distribution shown in Figure 7. This can be achieved using a diffuser designed with a coupling coefficient as shown in Figure 6.

Of particular importanc in the production of diffus rs is th ability to obtain an intensity distribution which does not exhibit directionality. Diffusers that use embedded scattering cent rs are not Lambertian emitters but rather are characterized by a cone of light emitted in the direction of propagation down the fiber with the fiber acting as a cylindrical axis. This directionality of the emitted light in these diffusers is problematic in for example photodynamic therapy (PDT) applications in respect of positioning the diffusers to irradiate the desired region of tissue.

The inventors have found that when the diffuser is comprised of a grating, the directionality in the azimuthal direction is improved as the planes of the grating tend to reflect a portion of light in the backward direction, thus greatly decreasing the bias towards forward scattering. However, due to the UV light being focussed onto the fiber from one side thereof during the writing of the grating, the intensity distribution of the light coupled out of the fiber is not very symmetrical about the fiber in the polar direction, rather a significant fraction of the light is coupled out in both polar directions in the plane containing the fiber and the incident UV laser beam. The inventors have discovered that this effect can be greatly reduced, resulting in a much more uniform polar distribution, by writing in the grating by illumination in one direction then rotating the fiber through an angle and repeating the writing process along the same length of the diffuser portion from another direction. The more times the fiber is rotated and the grating rewritten the more uniform the intensity distribution. For example, writing in the grating two times with the fiber rotated 90^0 between writings produces a diffuser with an intensity distribution more uniform than obtained with a grating written in once from one direction. Similarly, three writings with the fiber rotated 60^0 each time provides a slightly more uniform distribution than obtained with two rotations.

In order to avoid absorption of UV radiation by the protective buffer layer during the process of writing in the grating, the buffer is first removed. Once the

grating is writt n into the core a buffer lay r is reapplied over th fib r. Ref rring to Figure 8, in order to further improve the uniformity of the intensity distribution of light emitted from the diffuser, the polymer re-coat 150 preferably contains scattering centers 152 comprising micron or submicron sized, non-light absorbing particles such as silicon dioxide or titanium dioxide powder. The particles are thoroughly mixed with the polymer and the mixture is applied to the bare section of the fiber, where it is cured. Figure 8 shows the resulting milky-colored new buffer layer 150 containing the scattering centers further scatters and randomizes the light coupled out of the fiber core 14 thereby advantageously enhancing the uniformity of the intensity distribution both in the polar and azimuthal directions.

The improvement in the intensity distribution using diffusers having multiple written gratings and using a polymer re-coat containing particulates for scattering are shown in Figures 9a, 9b and 9c. Figure 9a is a polar plot of intensity distribution about the fiber diffuser with the grating written in once but with a polymer re-coat comprising SiO_2 powder. Figure 9b shows the azimuthal plot of intensity distribution for the same fiber as in Figure 9a. Figure 9c shows a combined polar and azimuthal plot of intensity distribution for a 3 mm length optical diffuser produced by writing the grating in twice, the grating being re-written the second time after the fiber was rotated 90^0 with respect to the laser beam. The fiber was re-coated after the grating was written in using a polymer comprising TiO_2 powder. The plot demonstrates the excellent angular uniformity achievable on combining the described methods.

Diffusers having specially tailored light distribution patterns along the length of the diffuser can be designed since the amount of light coupled out of the fiber is determined by the strength of the refractive index modulation. Regardless of the intensity of light radially emitted along the length of the diffuser portion, the present diffusers approximate Lambertian emitters.

Also, with the diffusers disclos d herein, light can b emitted over very long fiber l ngths (meters) albeit with very low light int nsiti s using typ I w ak gratings while on the other hand with type II strong gratings much higher intensities are achievable over shorter distances. The present multimode optical fiber diffusers disclosed herein have been produced having a length preferably in a range from about 1 mm to about 10 cm although longer gratings up to 50 cm can be readily fabricated.

The present fiber diffusers may be constructed with a diameter small enough to allow them to be fitted into housings or other functional devices such as endoscopes, catheters or thin hollow-bore needles (for example fiber diffusers can be produced with an outer diameter as small as 125 μm) for insertion into tissue/tumors. There are numerous biomedical applications of the fiber diffuser disclosed herein including photodynamic therapy (PDT) and other nonthermal therapeutic applications using light energy for medical procedures. The fibers may be attached to an outside surface of the catheter, or located on an interior of the catheter or integrated directly into the wall of the catheter. The fiber diffusers are capable of handling relatively high optical power since no absorbing materials are required in construction of the diffusers.

It will be understood that the optical fiber diffusers disclosed herein have applicability to numerous other technologies outside of biomedical applications, for example any application requiring light emitted along a desired length may be used.

In addition, multiple spaced isotropic diffusers may be written into any section of the fiber spaced from the end portion of the fiber. Figure 10 shows an embodiment of a fiber diffuser at 60 constructed in accordance with the present invention comprising a multimode fiber 62 having several diffuser sections 64 spaced along the fiber. Figure 11 shows another fiber diffuser at 70 wherein a portion of the cylindrical fiber 72 has been coated with a mirror 74 to reflect light that would be emitted from that portion of the fiber out of the uncoated portion.

An alt rnative m thod to fabricating optical diffus rs is to writ an appropriate density of scattering c nt rs in the fiber core. Referring to Figure 12, scattering cent rs 170 are produced point-by-point in the cor using a focussed UV laser beam to produce the scattering centers. The desirable intensity pattern of the diffuser can be achieved through point by point writing or by projecting the desired pattern using masks or image reduction techniques.

It will be understood by those skilled in the art that the present method of producing optical diffusers comprised of gratings or scattering centers within the optical fiber may also be used to provide a means of accessing the contents of the fiber. Writing a diffuser in a section of an optical fiber allows one to couple out at that point in the fiber some of the light signal propagating in the fiber. Thus the present invention provides a method of monitoring or testing, at any position in the fiber by creating a very short section of diffuser at that position. The emitted light signals would be detected using a detector and the signals interpreted using a signal processor.

It will also be understood by those skilled in the art that the optical diffusers disclosed herein may be used to produce sensors for detecting light incident on the fiber at any position along the diffuser portion of the fiber. The process of coupling a light signal back into the fiber is not highly efficient but nevertheless some of the light incident on the diffuser will be captured and will propagate and be guided along the fiber core to be interrogated by a detector. A sensor based on this type of configuration is very advantageous in, for example, hostile environments not amenable to expensive detectors.

The foregoing description of the preferred embodiments of the invention has been presented to illustrate the principles of the invention and not to limit the invention to the particular embodiments illustrated. It is intended that the scope of the invention be defined by all of the embodiments encompassed within the following claims and their equivalents.

THEREFORE WHAT IS CLAIMED IS:

1. An optical fib r diffuser device, comprising:

an optical fiber having a core and a cladding surrounding said core, a distribution of scattering centers embedded in said core along a preselected length thereof defining a diffuser portion, said distribution of scattering centers having an effective density along said preselected length of said core for coupling optical radiation radially outwards from said diffuser portion with a preselected intensity distribution as a function of distance along said preselected length of said diffuser portion.

2. The optical fiber diffuser device according to claim 1 wherein said optical fiber is a multimode optical fiber.

3. The optical fiber diffuser device according to claim 2 wherein said distribution of scattering centers includes a fiber grating comprising an effective modulated index of refraction profile along said preselected length of the core.

4. The optical fiber diffuser device according to claim 3 wherein said grating is one of a type I short period grating and a type II short period grating.

5. The optical fiber diffuser device according to claim 3 wherein said grating is one of a type I long period grating and a type II long period grating.

6. The optical fiber diffuser device according to claim 3 wherein the index of refraction profile is selected to produce a substantially uniform intensity output along the length of the diffuser portion.

7. The optical fiber diffuser d vic according to claim 3 wh rein the ind x of refraction profile is selected to produce a substantially Gaussian intensity output along the length of the diffuser portion.

8. The optical fiber diffuser device according to claim 3 wherein said diffuser portion is a first diffuser portion, and including at least two diffuser portions spaced apart along the optical fiber.

9. The optical fiber diffuser device according to claim 3 wherein a portion of the cladding surrounding said diffuser portion is coated with a mirror.

10. The optical fiber diffuser device according to claim 3 wherein the diffuser emits light with a substantially Lambertian intensity distribution.

11. The optical fiber diffuser device according to claim 3 wherein a buffer enveloping said preselected length defining said diffuser portion contains particles for scattering light coupled out of said core.

12. The optical fiber diffuser device according to claim 5 wherein a buffer enveloping said preselected length defining said diffuser portion contains particles for scattering light coupled out of said core.

13. The optical fiber diffuser device according to claim 5 wherein a buffer enveloping said preselected length defining said diffuser portion contains particles for scattering light coupled out of said core.

14. The optical fiber according to claim 11 wherein said particles have mean diameters in a range from submicrons to microns, and wherein said particles are substantially nonabsorbing.

15. The optical fiber diffus r device according to claim 3 wherein said grating is a chirped grating.

16. The optical fiber diffuser device according to claim 3 wherein said diffuser portion has a length in a range from about 1 mm to about 50 cm.

17. An optical fiber diffuser device for delivery of light energy, comprising:

a multimode optical fiber having a core and a cladding surrounding said core, a distribution of scattering centers embedded in said core along a preselected length thereof defining a diffuser portion, said distribution of scattering centers having an effective density along said preselected length of said core for coupling optical radiation radially outwards from said diffuser portion with a preselected intensity distribution as a function of distance along said preselected length of said diffuser portion; and

a source of optical radiation connected to one end of the multimode optical fiber.

18. The device according to claim 17 wherein said distribution of scattering centers includes a fiber grating comprising an effective modulated index of refraction profile along said preselected length of the core.

19. The device according to claim 18 wherein said grating is one of a type I short period grating and a type II short period grating.

20. The device according to claim 18 wherein said grating is one of a type I long period grating and a type II long period grating.

21. The devic according to claim 18 wherein said diffuser portion is a first diffuser portion, and including at l ast two diffuser portions spaced apart along the optical fiber, each diffuser portion including a type II grating.

22. The device according to claim 18 wherein the the index of refraction profile is modulated to produce a substantially Lambertian intensity distribution along the length of the diffuser portion.

23. The device according to claim 18 wherein the index of refraction profile is modulated to produce a substantially uniform intensity output along the length of the diffuser portion.

24. The device according to claim 18 wherein the index of refraction profile is modulated to produce a substantially Gaussian intensity output along the length of the diffuser portion.

25. The device according to claim 18 including a housing holding at least a portion of the optical fiber.

26. The device according to claim 25 including adjustment means for extending and retracting the diffuser portion of the optical fiber.

27. The device according to claim 26 wherein the housing is a hollow-bore needle.

28. The device according to claim 26 wherein the housing is an endoscope.

29. The d vice according to claim 25 wh rein said housing is a cathet r, said fiber being attached to an outside surface of said cath ter, or located on an interior of said catheter or built into a wall of said catheter.

30. A method of producing an optical fiber diffuser device, comprising:

providing an optical fiber having a core and a cladding surrounding said core; and

calculating a coupling coefficient to produce a preselected intensity distribution of optical radiation to be radially emitted along a preselected length of the optical fiber; and

producing at least one distribution of scattering centers having an effective density along said preselected length of the core of the optical fiber for coupling optical radiation radially outwards from said diffuser portion with said preselected intensity distribution as a function of distance along the length of the diffuser portion.

31. The method according to claim 30 wherein said optical fiber is a multimode optical fiber.

32. The method according to claim 31 wherein said distribution of scattering centers includes a fiber grating comprising an effective modulated index of refraction profile along said preselected length of the core.

33. The method according to claim 32 wherein said grating is one of a type I short period grating and a type II short period grating.

34. The method according to claim 32 wherein said grating is one of a type I long period grating and a type II long period grating.

35. The method according to claim 32 wherein said fiber grating is produced using an amplitude mask.

36. The method according to claim 35 wherein said amplitude mask is a chirped amplitude mask.

37. The method according to claim 32 wherein said effective modulated index of refraction profile along said preselected length of the core is produced by aligning said fiber behind the amplitude mask illuminating said preselected length of the core through said amplitude mask for an effective period of time.

38. The method according to claim 37 wherein after illuminating said preselected length of the core said optical fiber is rotated a preselected amount and said preselected length of the core is irradiated for said effective period of time.

39. The method according to claim 31 wherein said coupling coefficient is selected to give a substantially uniform intensity distribution along the length of the diffuser portion.

40. The method according to claim 31 wherein said coupling coefficient is selected to give a Gaussian intensity distribution along the length of the diffuser portion.

41. The method according to claim 31 wherein the step of producing at least one diffuser portion includes producing a plurality of diffuser portions spaced along the optical fiber.

42. An optical sensor, comprising:

a light d tection means; and

an optical fiber connected to the light detection means, the optical fiber having a core and a cladding surrounding said core and including at least one distribution of scattering centers in a preselected length of the core, said distribution of scattering centers having an effective density along said preselected length of said core for optically coupling a fraction of light incident on the diffuser portion into the core which is transmitted to said light detection means.

43. The sensor according to claim 42 wherein said distribution of scattering centers includes a fiber grating comprising an effective modulated index of refraction profile along said preselected length of the core.

44. The sensor according to claim 43 wherein said grating is one of a type I short period grating and a type II short period grating.

45. The sensor according to claim 43 wherein said grating is one of a type I long period grating and a type II long period grating.

46. A method of monitoring light signals transmitted along an optical fiber, comprising:

forming a distribution of scattering centers in a preselected length of an optical fiber, the distribution of scattering centers having an effective coupling strength to couple some of the light transmitted along core of the fiber out of the fiber and having an effective modulated index of refraction along the preselected length to give a desired intensity distribution of light emitted radially from said fiber; and

detecting light emitted from said fiber.

47. Th method according to claim 46 including using signal processing means to interpret the light emitted from said fiber.

48. The method according to claim 47 wherein said distribution of scattering centers includes a fiber grating comprising an effective modulated index of refraction profile along said preselected length of the core.

49. The method according to claim 48 wherein said grating is one of a type I short period grating and a type II short period grating.

50. The method according to claim 48 wherein said grating is one of a type I long period grating and a type II long period grating.

51. The optical fiber diffuser device according to claim 1 wherein said optical fiber is a single mode optical fiber, and wherein said fiber grating is one of a type I short period grating, a type II short period grating, a type I long period grating and a type II long period grating.

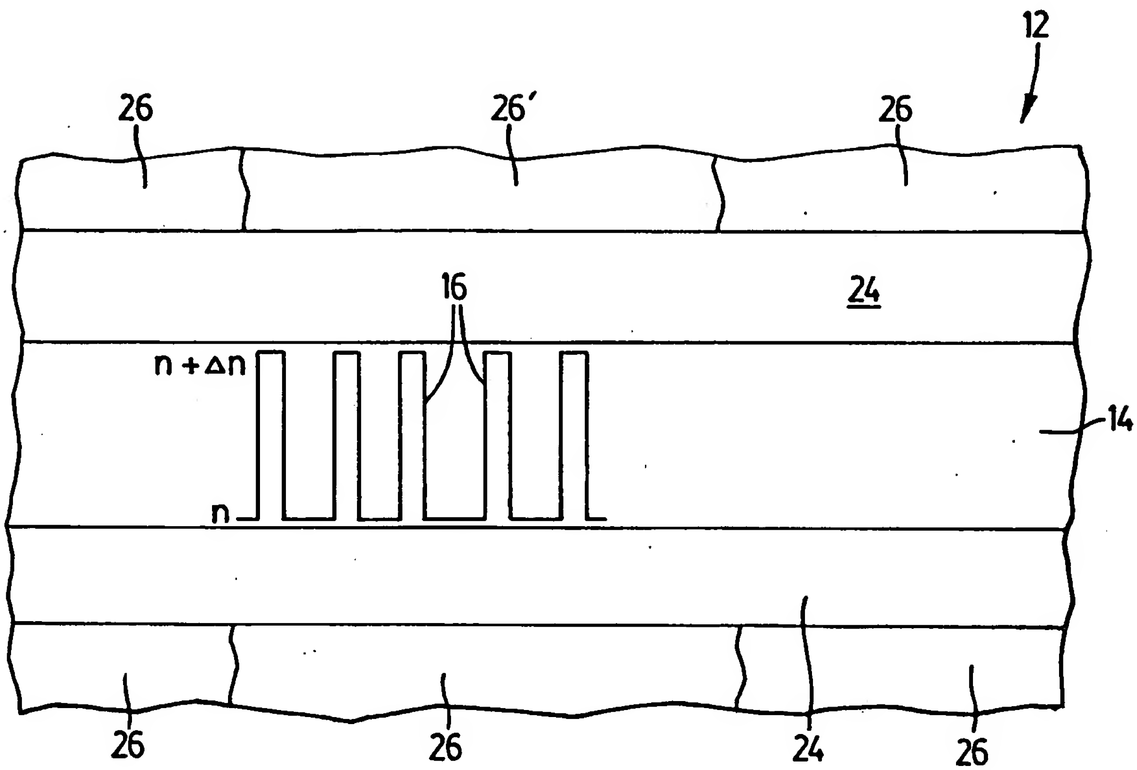
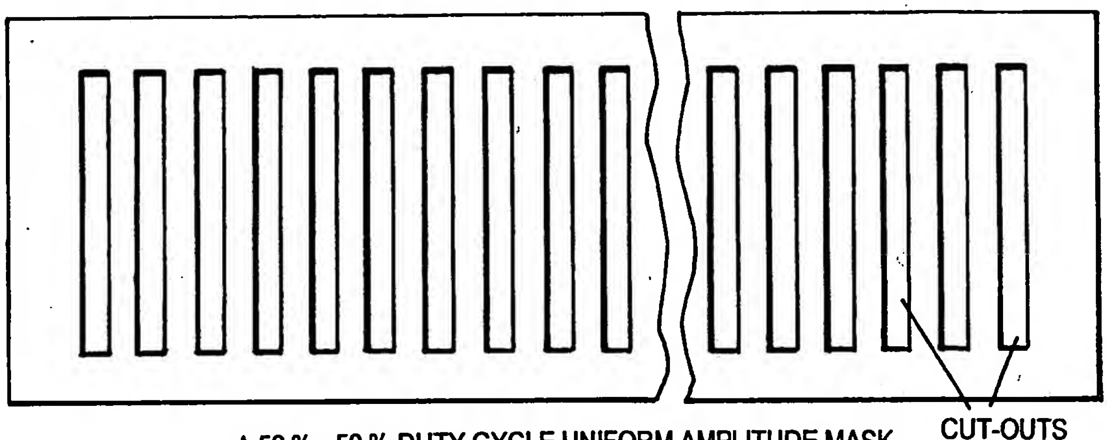
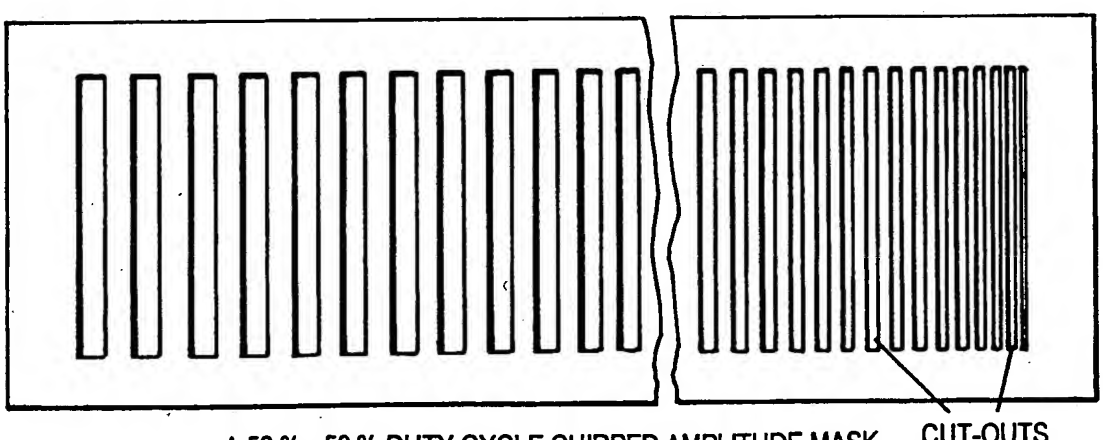


FIG. 1



A 50 % - 50 % DUTY CYCLE UNIFORM AMPLITUDE MASK

FIG. 2



A 50 % - 50 % DUTY CYCLE CHIRPED AMPLITUDE MASK

FIG. 3

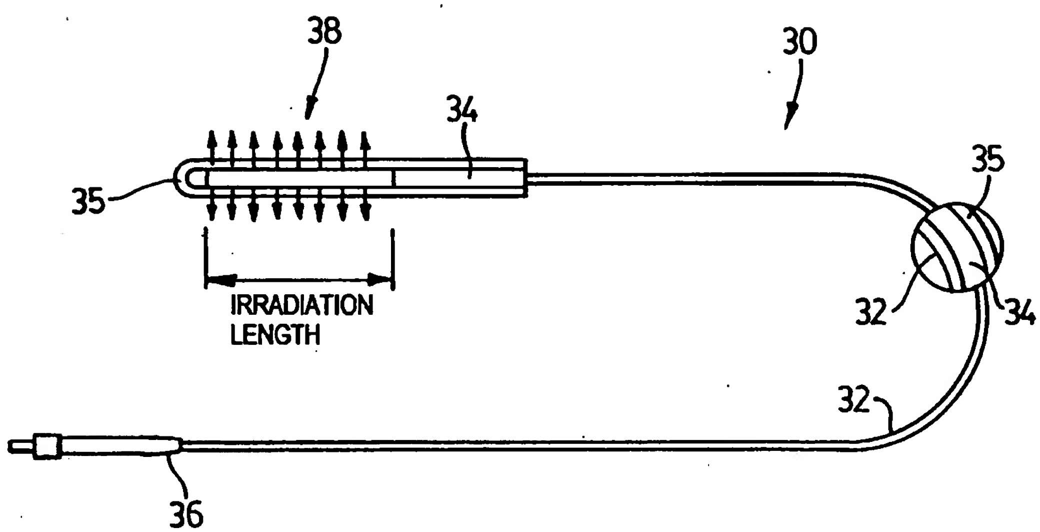


FIG. 4

COUPLING COEFFICIENT AS A FUNCTION OF POSITION FOR A UNIFORM FIBER DIFFUSER

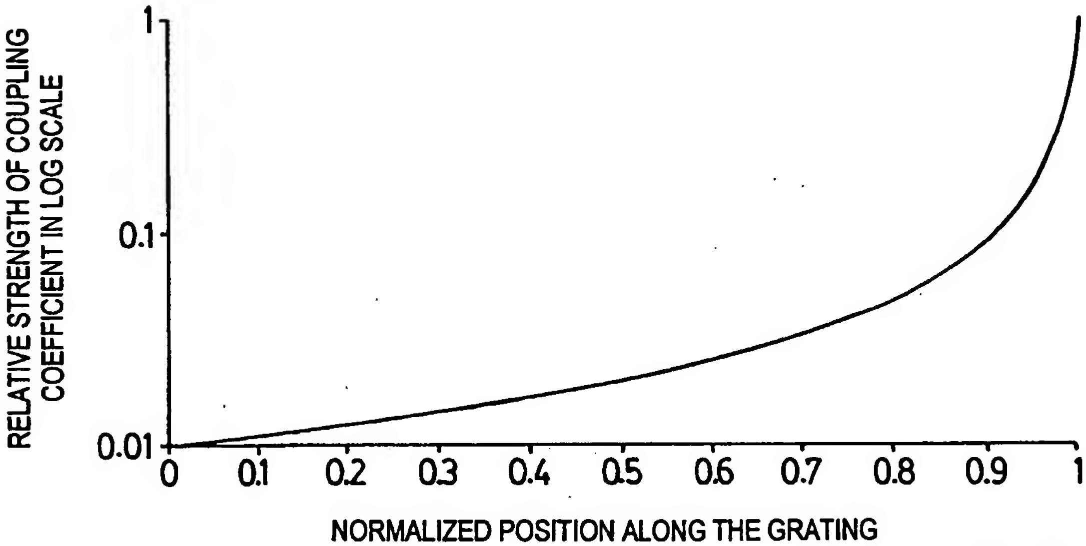


FIG. 5a

INTENSITY DISTRIBUTION ALONG A UNIFORM FIBER DIFFUSER

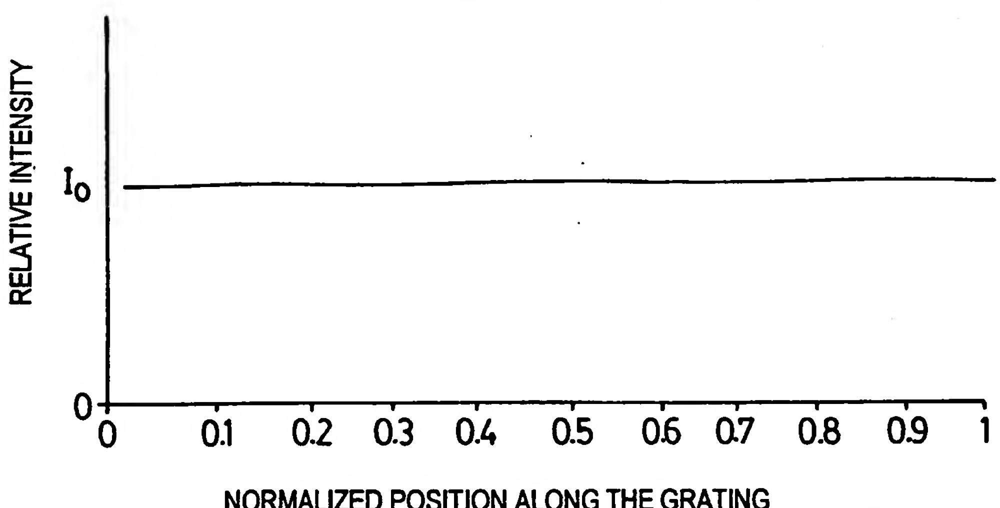


FIG. 5b

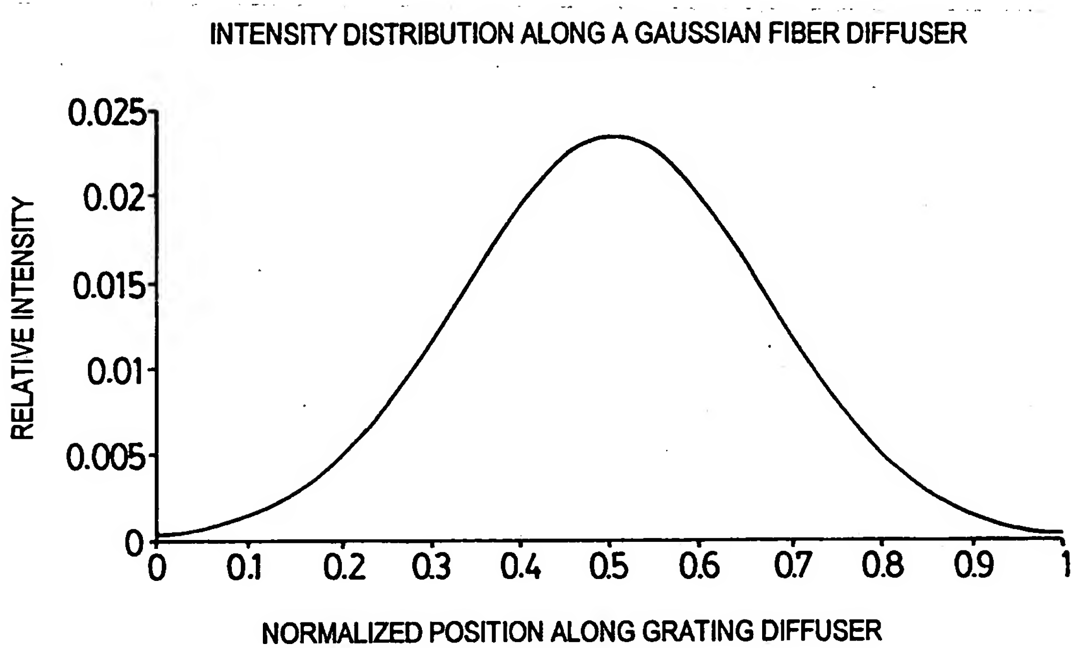

INTENSITY DISTRIBUTION ALONG A GAUSSIAN FIBER DIFFUSER
RELATIVE INTENSITY
0.025
0.02
0.015
0.01
0.005
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
NORMALIZED POSITION ALONG GRATING DIFFUSER

FIG. 6

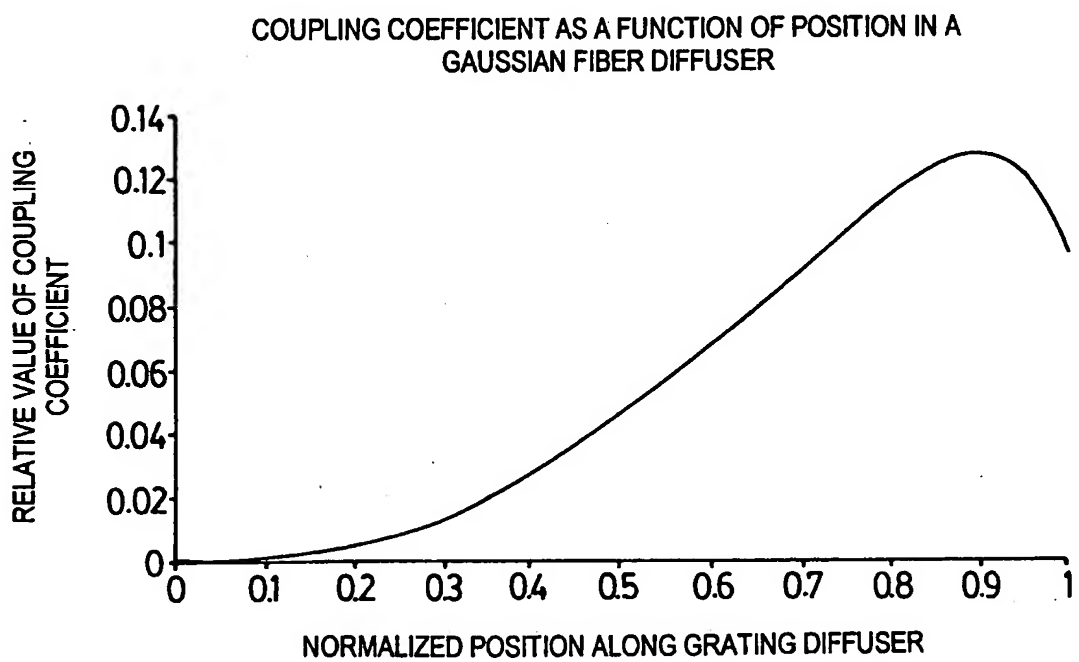
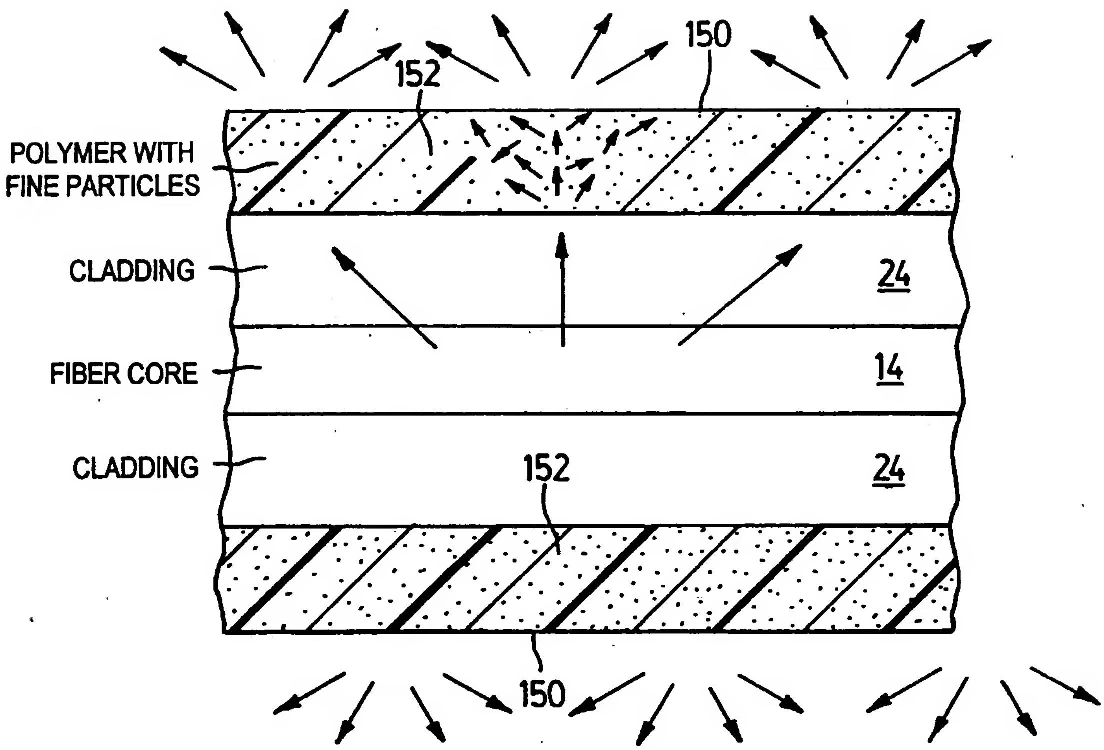

COUPLING COEFFICIENT AS A FUNCTION OF POSITION IN A GAUSSIAN FIBER DIFFUSER
RELATIVE VALUE OF COUPLING COEFFICIENT
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
NORMALIZED POSITION ALONG GRATING DIFFUSER

FIG. 7



LIGHT SCATTERING EFFECT OF THE RE-COATING OF FIBER LIGHT DIFFUSER WITH POLYMER EMBEDDED WITH FINE PARTICLES

FIG. 8

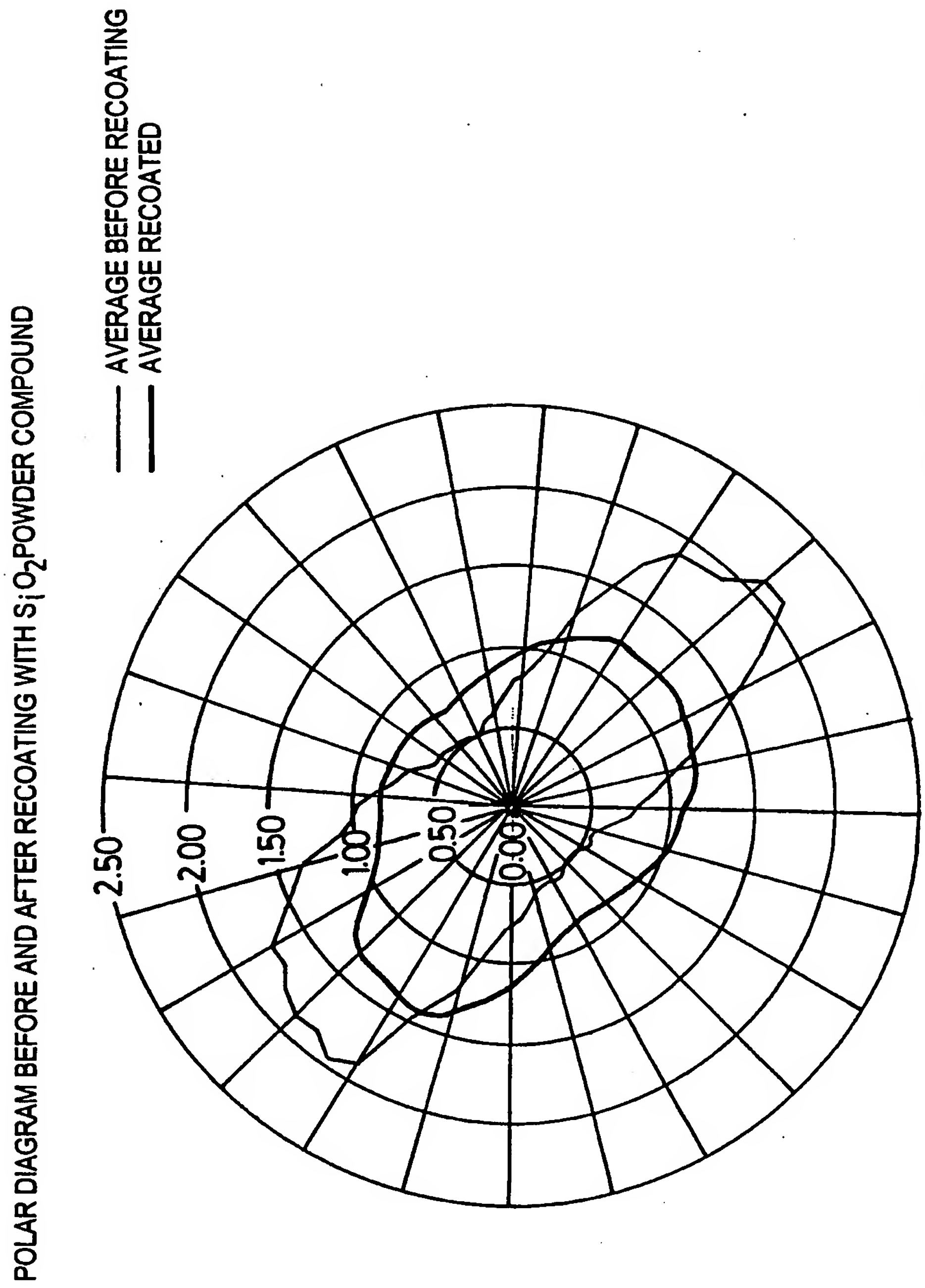

POLAR DIAGRAM BEFORE AND AFTER RECOATING WITH S_iO_2 POWDER COMPOUND
AVERAGE BEFORE RECOATING
AVERAGE RECOATED
2.50
2.00
1.50
1.00
0.50
0.00

FIG. 9a

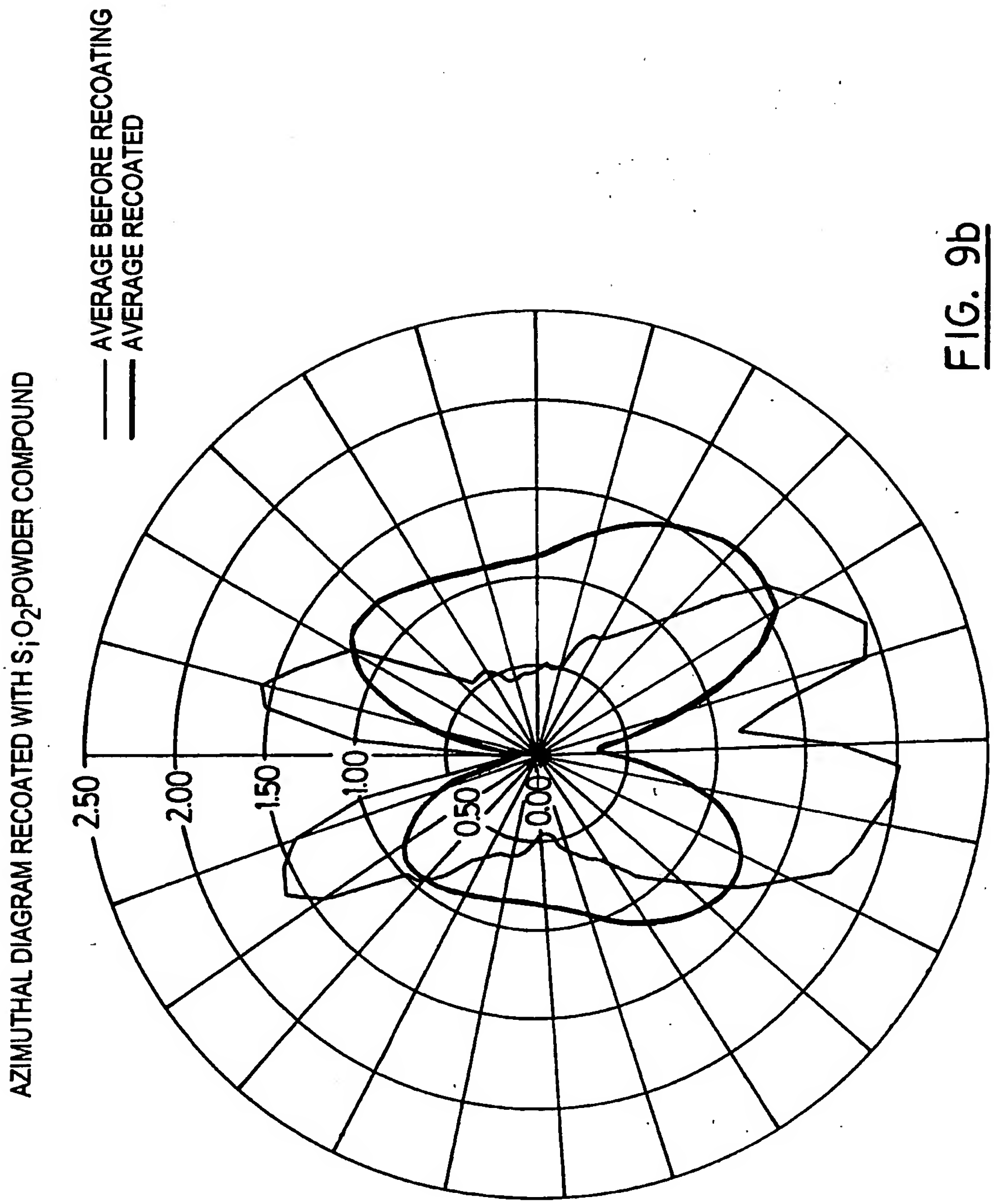

AZIMUTHAL DIAGRAM RECOATED WITH S_iO_2POWDER COMPOUND
AVERAGE BEFORE RECOATING
AVERAGE RECOATED
2.50
2.00
1.50
1.00
0.50
0.00

FIG. 9b

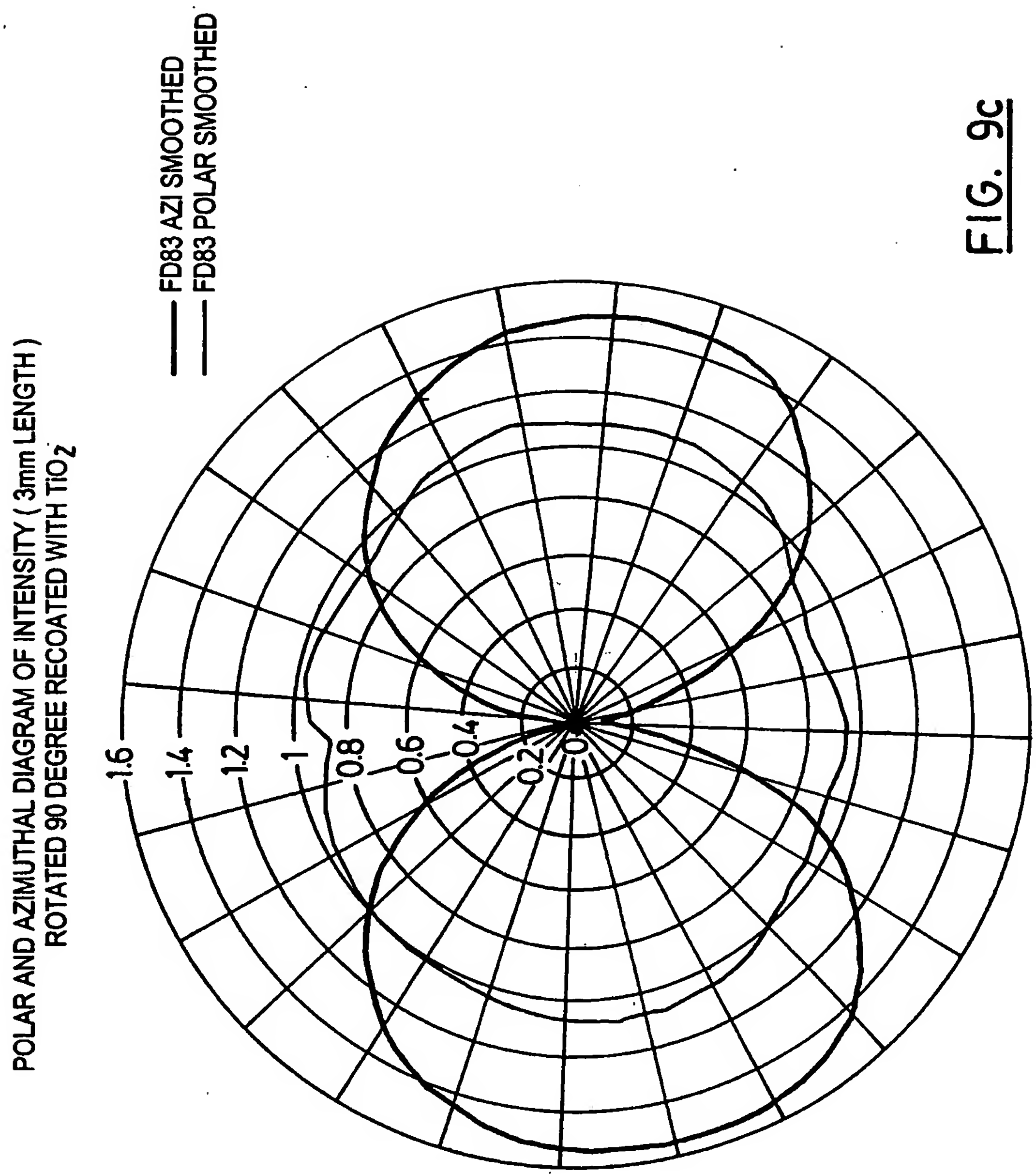

POLAR AND AZIMUTHAL DIAGRAM OF INTENSITY (3mm LENGTH)
ROTATED 90 DEGREE RECOATED WITH TiO_2
FD83 AZI SMOOTHED
FD83 POLAR SMOOTHED
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0

FIG. 9c

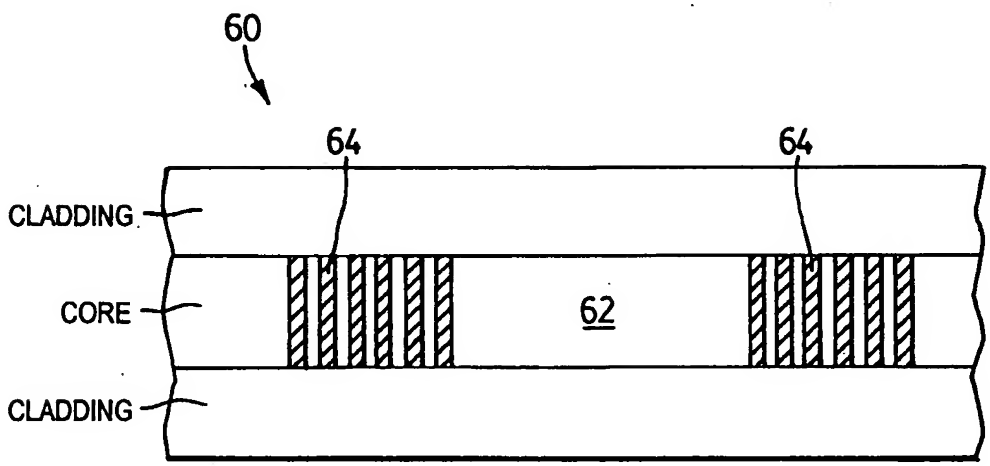


FIG. 10

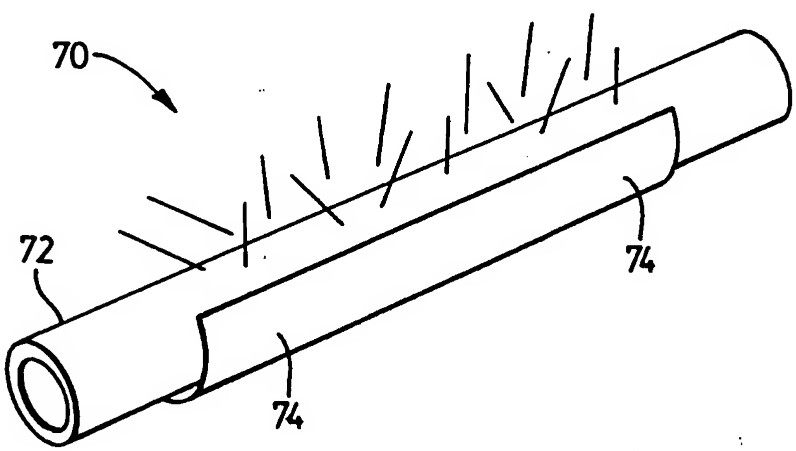


FIG. 11

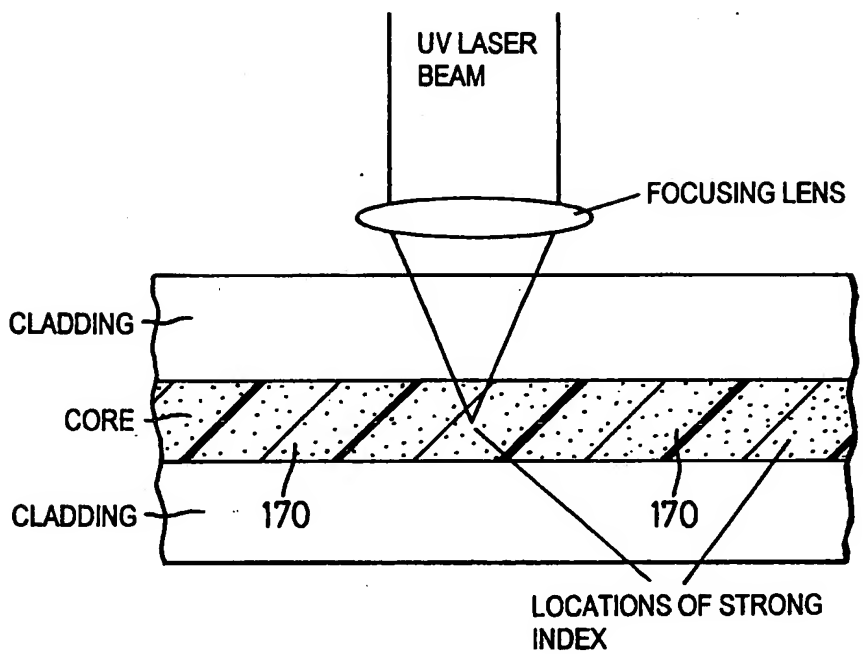

UV LASER
BEAM
FOCUSING LENS
CLADDING
CORE
CLADDING
170
170
LOCATIONS OF STRONG
INDEX

FIG. 12

INTERNATIONAL SEARCH REPORT

International Application No
PCT/CA 00/00733

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 G02B6/16 F21V8/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 G02B F21V

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	WO 99 23041 A (MIRAVANT SYST INC ;RYCHNOVSKY STEVEN J (US); SHINN MICHAEL G (US)) 14 May 1999 (1999-05-14) page 9 -page 11; figures 1-3,5	1,2,17, 30,31, 39,41 3,4,6,8, 15,18, 19,21, 23-25, 32,33, 35-37

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"P" document published prior to the international filing date but later than the priority date claimed

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
17 October 2000	27/10/2000

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	von Moers, F

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/CA 00/00733

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
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X	EP 0 273 311 A (FIBERSTARS INC) 6 July 1988 (1988-07-06)	1,2,17, 30,31
A	column 3, line 40 -column 4, line 16; figure 1	3,6,18, 32
A	EP 0 874 191 A (BRIDGESTONE CORP) 28 October 1998 (1998-10-28) column 6, line 37 - line 44; figure 7	9
A	US 4 422 719 A (ORCUTT DONALD E) 27 December 1983 (1983-12-27) column 5, line 14 - line 22; figure 5	11-13
X	EP 0 438 759 A (UNITED TECHNOLOGIES CORP) 31 July 1991 (1991-07-31) column 7, line 36 -column 8, line 26; figure 3	42-44, 46,48
A	US 4 733 929 A (BROWN DAVID C) 29 March 1988 (1988-03-29) column 2, line 46 -column 3, line 18; figure 1	42
X	EP 0 840 150 A (LUCENT TECHNOLOGIES INC) 6 May 1998 (1998-05-06) column 4, line 20 - line 58; figures 1-3	46-49,51

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/CA 00/00733

Patent document cited in search report		Publication date	Patent family member(s)		Publication date
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			JP 4288510	A	13-10-1992
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			JP 10133054	A	22-05-1998
			US 6002822	A	14-12-1999
			US 5850302	A	15-12-1998

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Summary

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Total (1)	41	41	0	-